

Updated Big Bang Nucleosynthesis confronted to WMAP observations and to the Abundance of Light Elements

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ABSTRACT

We improve Standard Big Bang Nucleosynthesis (SBBN) calculations taking into account new nuclear physics analyses (Descouvemont et al. 2003). Using a Monte-Carlo technique, we calculate the abundances of light nuclei (D , ${}^3\text{He}$, ${}^4\text{He}$ and ${}^7\text{Li}$) versus the baryon to photon ratio. The results concerning $\Omega_b h^2$ are compared to relevant astrophysical and cosmological observations : the abundance determinations in primitive media and the results from CMB experiments, especially the WMAP mission. Consistency between WMAP, SBBN results and D/H data strengthens the deduced baryon density and has interesting consequences on cosmic chemical evolution. A significant discrepancy between the calculated ${}^7\text{Li}$ deduced from WMAP and the Spite plateau is clearly revealed. To explain this discrepancy three possibilities are invoked : systematic uncertainties on the Li abundance, surface alteration of Li in the course of stellar evolution or poor knowledge of the reaction rates related to ${}^7\text{Be}$ destruction. In particular, the possible role of the up to now neglected ${}^7\text{Be}(d,p)2\alpha$ and ${}^7\text{Be}(d,\alpha){}^5\text{Li}$ reactions is considered. Another way to reconcile these results coming from different horizons, consists to invoke, speculative, new primordial physics which could modify

the nucleosynthesis emerging from the Big Bang and perhaps the CMB physics itself. The impressive advances in CMB observations provide a strong motivation for more efforts in experimental nuclear physics and high quality spectroscopy to keep BBN in pace.

Subject headings: Primordial nucleosynthesis, Cosmological parameters, Nuclear rates

1. Introduction

There exist different ways to determine the baryonic density of the Universe. The "traditional method" is Standard Big-Bang Nucleosynthesis (SBBN) which is based on nuclear physics in the early universe. This calculation reproduces the primordial light element (D , 3He , 4He and 7Li) abundances over an interval of 10 orders of magnitude. Recently, however, the study of the Cosmic Microwave Radiation (CMB) anisotropies and the census of the Lyman- α forest at high redshift have provided new methods to obtain $\Omega_b h^2$. In the case of the CMB, the baryonic parameter ($\Omega_b h^2$, where h is the Hubble parameter expressed in units of $100 \text{ km.s}^{-1}.\text{Mpc}^{-1}$) is extracted from the amplitudes of the acoustic peaks in the angular power spectrum of the anisotropies. The $\Omega_b h^2$ values deduced from these three different methods are in rather good agreement but may not be totally model independent.

A series of data have been released by many experiments, but very recently, the WMAP mission has delivered a wealth of results, based on the first year of observations (Spergel et al. 2003). The mean value $\Omega_b h^2 = 0.024 \pm 0.001$ agrees with the previous estimates but the error bar is considerably reduced. When including constraints from other observations at complementary angular scales, the value $\Omega_b h^2 = 0.0224 \pm 0.0009$ is obtained (Spergel et al. 2003), setting stringent constraints on the general discussion of the BBN scenario.

In the case of the Lyman- α forest, the baryonic density is deduced from the study of the atomic HI and HeII Lyman- α absorption lines observed on the line of sight to quasars (baryonic matter distributed on large scales, in the redshift range $0 < z < 5$). Indeed, this evaluation, though indirect because of the relatively large ionization uncertainties, leads to results consistent with the two other methods ($\Omega_b h^2 \sim 0.02$, Riedeger et al. 1998). However, the baryonic density obtained in this way carries a relatively large error bar, which in the present context makes it less constraining.

Consequently, due to the large efforts made recently to determine the cosmological parameters, it is now mandatory to refine the BBN analysis. In this paper, we update the study performed in Coc et al. (2002) where we had exploited a set of reaction rates from the

NACRE compilation (Angulo et al. 1999). We reconsider here the BBN calculation using reaction rates obtained from a new analysis of the ten most important nuclear reactions (Descouvemont et al. 2003, hereafter DAA). Moreover, we consider the impact on the BBN results of these main reactions and, at the same time, study other reactions which could be potentially important for SBBN.

After a summary of the observational data concerning the light isotope abundances and the new nuclear input, we use Monte-Carlo calculations to obtain the abundances of light nuclei (D , 3He , 4He and 7Li) versus the baryon to photon ratio, taking into account the uncertainties on nuclear reaction rates. We discuss both agreements and discrepancies confronting calculations, abundance data and WMAP results.

2. Abundances of light elements

The observation of the most primitive astrophysical sites in which abundances can be measured and their confrontation to the BBN calculations allow to extract $\Omega_b h^2$. For a general discussion on the updated observational data, see the review of Olive (2003).

The primordial 4He abundance, Y_P , is derived from observations of metal-poor, extragalactic, ionized hydrogen (HII) regions.

We adopt here the two recent values of Izotov et al. (1999), ($Y_P = 0.2452 \pm 0.0015$) and Luridiana et al. (2003), ($Y_P = 0.2391 \pm 0.0020$), giving a relatively large range of abundance for this isotope. Indeed, when considering systematic uncertainties, Fields and Olive (1998) obtain the range $Y_P = 0.238 \pm 0.002 \pm 0.005$,

Deuterium is particularly fragile and is only destroyed in stellar processes. Hence, the primordial abundance should be represented, in principle, by the highest value observed in remote cosmological clouds on the line of sight of high redshift quasars. This is what we adopted in Coc et al. (2002) (hereafter CV). However, recently, Kirkman et al. (2003) have obtained a new measurement of $D/H = (2.42^{+0.35}_{-0.25}) \times 10^{-5}$ and $[O/H] = -2.79 \pm 0.05$. They give also their best estimate of the primordial D abundance, averaging individual measurements toward five QSOs, namely $D/H = (2.78^{+0.44}_{-0.38}) \times 10^{-5}$ that we now adopt here. However, as the sample of cosmological clouds is very limited and the systematic errors on D/H values are hard to estimate, this value has to be considered with caution. Indeed, Crighton et al. (2003) highlight important aspects of the analysis which were not explored in previous works showing that the methods used in analyses of D/H in quasar spectra should be improved. For example, according to different hypotheses about contamination, they show that D/H in the absorber toward QSO PG 1718+4807 can be as high as 4.2×10^{-4}

or significantly lower than $3. \times 10^{-4}$.

Since the discovery of the Spite plateau (Spite and Spite 1982), namely the constant lithium abundance as a function of metallicity, many new observations have strengthened its existence. Ryan et al. (1999, 2000) have obtained a tight limit on the plateau abundance. Specifically, these authors take into account all possible contributions from extrapolation to zero metallicity, ${}^7\text{Li}$ depletion mechanisms and biases in the analysis. Their extrapolated value (at 95% confidence level) is : $\text{Li}/H = (1.23_{-0.32}^{+0.68}) \times 10^{-10}$. Recently, Thévenin et al. (2001) have obtained VLT - UVES high resolution spectra of seven metal poor stars in the globular cluster, NGC 6397. Their mean value of lithium, $A(\text{Li}) = 2.23 \pm 0.07$, is consistent with the preceding one. Bonifacio et al. (2002) who have also observed this globular cluster, obtain a higher mean value : $A(\text{Li}) = 2.34 \pm 0.056$. The difference between these two evaluations lies in the different effective temperatures adopted. Indeed, these two independent observations and analyses give an indication of the systematic errors involved in Li/H determination.

Both observers and experts of stellar atmospheres agree to consider that the abundance determination in halo stars, and more particularly that of lithium require a sophisticated analysis . In this respect, the temperature scale is influential and it is possible that the scale adopted by Ryan et al. (2000) underestimates the Li/H ratio. Moreover, the determination of Li/H in stars embedded in globular clusters is more questionable than in the halo field stars since globular cluster stars may be polluted by their environment. So, it would be necessary to select in a first step, star by star, those which are the less contaminated, i.e., the most adequate to give a reliable Li/H abundance. Note, however, that stars from small globular clusters (as NGC 6397) are representative of the halo stars (Cayrel, private communication). In addition to the Ryan et al. range, adopted here as in CV, we will also consider, conservatively, the upper limit of the Bonifacio et al. (2002) value, namely $\text{Li}/H = 2.49 \times 10^{-10}$. Note however that these globular cluster determinations, at $[\text{Fe}/\text{H}] \approx -2$, cannot be directly compared to the Ryan et al. (2000) extrapolated value.

${}^3\text{He}$ has been measured recently by Bania et al. (2002) in HII regions, but due to the large scatter in the data and the complex galactic history of this isotope, we cannot consider it as a good cosmological tracer (Vangioni-Flam et al. 2003).

3. SBBN with improved nuclear input

In our previous work (CV), we performed Monte-Carlo calculations to obtain statistical limits on the calculated abundances, using mainly the NACRE compilation of reaction rates

(Angulo et al. 1999). One of the main innovative features of NACRE with respect to former compilations (Caughlan and Fowler 1988, hereafter CF88) is that uncertainties are analyzed in detail and realistic lower and upper bounds for the rates are provided. However, since it is a general compilation for multiple applications, coping with a broad range of nuclear configurations, these bounds have not always been evaluated through a rigorous statistical methodology. Hence, in CV, a simple uniform distribution between these bounds was assumed for the Monte–Carlo calculations. Since this compilation was not specifically addressed to the nuclear reactions implied in the BBN it had also to be complemented by other sources (Smith et al. 1993, Brune et al. 1999). Two recent SBBN calculations have been made with updated reaction rates, one based on the Nollett and Burles (2000) compilation (hereafter NB) and another (Cyburt et al. 2001; hereafter CFO) on a partial, reanalysis the NACRE compiled data. These works (NB and CFO) have given better defined statistical limits for the reaction rates of interest for SBBN. One (NB) has used spline functions to fit the astrophysical S –factors (see definition in CV) while the other (CFO) have used the NACRE S –factors with a different normalization (restricted to BBN energies.) In NACRE, data are in general fitted either by Breit–Wigner formula (the shape of nuclear resonances) or by low order polynomial for non-resonant contributions. Indeed, unlike in CFO, the fits are not restricted to the energy range of BBN, taking advantage of all data to constrain the nuclear factor. The use of low order polynomials, or better theoretical S –factors shapes, rather than e.g. splines, has the advantage of smoothing out the dispersion of data arising from the measurement technique itself rather than from physics when no sharp resonance is expected in the energy domain. Consequently, the CFO global normalization factors are different from those of NACRE. One should note, however, the isotope yields obtained from BBN calculations using the two compilations (NACRE and NB) agree well, reinforcing the confidence in these analyses.

Nevertheless, in order to improve on the general NACRE compilation, DAA have reassessed carefully the main nuclear network (ten reactions) on the basis of an R–Matrix analysis. The R–matrix theory has been used for many decades in the nuclear physics community. It allows to parametrize nuclear cross sections with a reduced set of parameters related to nuclear quantities such as resonance energies and partial widths. This method can be used for both resonant and non-resonant contributions to the cross section. (See DAA and reference therein for details of the method.) The energy dependence of the fitted S –factors is now constrained by the Coulomb functions and R–matrix poles, rather than by arbitrary polynomial or spline functions. Even though this method has been widely used in nuclear astrophysics (see e.g. Barker & Kajino 1991 for a recent application to a nuclear astrophysics problem), this is the first time that it is applied to SBBN reactions. In addition, this new compilation (DAA) provides $1\text{--}\sigma$ statistical limits for each of the 10 rates: ${}^2\text{H}(\text{p},\gamma){}^3\text{He}$, ${}^2\text{H}(\text{d},\text{n}){}^3\text{He}$,

$^2\text{H}(\text{d,p})^3\text{H}$, $^3\text{H}(\text{d,n})^4\text{He}$, $^3\text{H}(\alpha, \gamma)^7\text{Li}$, $^3\text{He}(\text{n,p})^3\text{H}$, $^3\text{He}(\text{d,p})^4\text{He}$, $^3\text{He}(\alpha, \gamma)^7\text{Be}$, $^7\text{Li}(\text{p},\alpha)^4\text{He}$ and $^7\text{Be}(\text{n,p})^7\text{Li}$. These rate limits are derived from the R–Matrix parameter errors calculated during the fitting procedure (see DAA). The two remaining reactions of importance, $\text{n} \leftrightarrow \text{p}$ and $^1\text{H}(\text{n},\gamma)^2\text{H}$ (Chen and Savage 1999) come from theory and are unchanged with respect to CV.

We have re–done our Monte-Carlo calculations using this time Gaussian distributions with parameters provided by the new compilation (DAA) discussed above. We have calculated the mean and the variance of the ^4He , D , ^3He and ^7Li yields as a function of η , fully consistent with our previous analysis (CV). The differences with CFO for the ^7Li yield is probably due to their renormalization procedure of NACRE S–factors. Figure 1 displays the resulting abundance limits ($1\text{-}\sigma$) [it was $2\text{-}\sigma$ in Fig.4 of CV] from SBBN calculations compared to primordial ones inferred from observations. It is important to note that the present results are in good agreement with CV. With these improved calculations, we can now compare SBBN results, primitive abundances of the light elements and baryonic density derived from CMB observations.

4. Discussion

Following numerous determinations of $\Omega_b h^2$ through CMB observations, WMAP observations and subsequent analyses, including other observational constraints, have delivered a very precise value, $\Omega_b h^2 = 0.0224 \pm 0.0009$, corresponding to $\eta = (6.14 \pm 0.25) \times 10^{-10}$ (Spergel et al. 2003). In their paper, this evaluation has been compared to the BBN calculations of Burles et al. (2001), leading to $D/H = (2.62^{+0.18}_{-0.2}) \times 10^{-5}$. With our improved analysis of SBBN reaction rates, using the WMAP $\Omega_b h^2$ range together with these SBBN results (WMAP+SBBN hereafter), we can also deduce the primordial abundances as shown in Figure 1 where is represented the WMAP $\Omega_b h^2$ range intercepting the SBBN yield curves. The uncertainties on these abundances take into account the WMAP $\Omega_b h^2$ uncertainty and the SBBN uncertainties from DAA reaction rates. Our WMAP+SBBN deuterium primordial abundance is $D/H = (2.60^{+0.19}_{-0.17}) \times 10^{-5}$ which is in perfect agreement with the average value $(2.78^{+0.44}_{-0.38}) \times 10^{-5}$ (Kirkman et al. 2003) of D/H observations in cosmological clouds. The other primordial abundances deduced from WMAP+SBBN are $Y_P = 0.2479 \pm 0.0004$ for the ^4He mass fraction, $^3\text{He}/H = (1.04 \pm 0.04) \times 10^{-5}$ and $^7\text{Li}/H = (4.15^{+0.49}_{-0.45}) \times 10^{-10}$. Recently, Cyburt et al. (2003) have also compared BBN and WMAP data. Their mean D/H value (2.75×10^{-5}) is slightly higher than our result while Y_P is in good agreement. More important, their predicted ^7Li (3.82×10^{-10}) is lower than our prediction (about 11%; see Table 1). The reason is probably due to the different normalization for nuclear data as

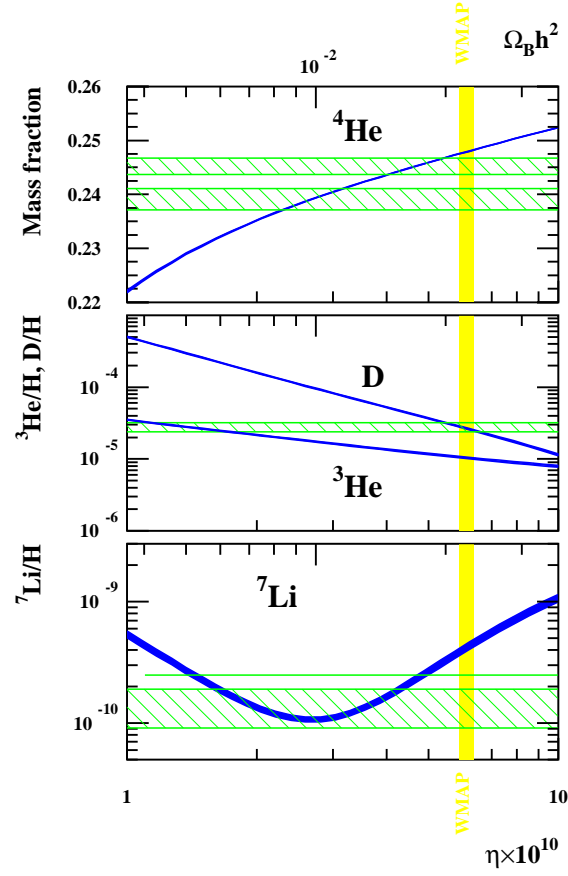


Fig. 1.— Abundances of ^4He (mass fraction), D , ^3He and ^7Li (by number relative to H) as a function of the baryon over photon ratio η or $\Omega_b h^2$. Limits ($1\text{-}\sigma$) are obtained from Monte Carlo calculations. Hatched area represent primordial ^4He , D and ^7Li abundances deduced from different primitive astrophysical sites (see Section 2): Izotov et al. (1999) (high area) and Luridiana et al. (2003) (low area) for ^4He , Kirkman et al. (2003) for D , and Ryan et al. (2000) for ^7Li (95% c.l.). Concerning ^7Li , we also show an upper limit derived from Bonifacio et al. (2002) observations (dashed line). The vertical stripe represents the ($1\text{-}\sigma$) $\Omega_b h^2$ limits provided by WMAP (Spergel et al. 2003).

discussed above. It is timely to confront these primordial nucleosynthesis results with the observations described in Section 2 and to explore various astrophysical consequences.

4.1. Helium

As said previously, the ${}^4\text{He}$ abundance determinations in HII regions are quite unsatisfactory due to observational uncertainties and the complex physics of HII regions. Luridiana et al. (2003) obtained a new determination of Y_P , based on the abundance analysis of five metal poor extragalactic HII regions. This relatively low value (0.2391 ± 0.002) differs significantly from the Isotov et al. (1999) higher value (0.2452 ± 0.0015) and the one deduced from BBN+WMAP (0.2479), but systematic uncertainties may prevail due to observational difficulties and complex physics (Fields and Olive, 1998). In fact, the Izotov et al. interval (Section 2 and Fig. 1) is only marginally compatible with the WMAP observations. ($\sim 8\%$ probability).

4.2. Deuterium

WMAP observations together with our SBBN calculations lead to the mean primordial D/H value of 2.60×10^{-5} . In Fig. 2 we plot D/H observations at high redshift (Burles & Tytler, 1998; Tytler et al. 1996; O’Meara et al. 2001, D’Odorico et al. 2001; Pettini & Bowen 2001; Kirkman et al. 2003) which are thought to be representative of the D primordial abundances together with those inferred from SBBN calculations and $\Omega_b h^2$ range from WMAP. The stripe widths represent the uncertainty ($1\text{-}\sigma$) originating from both the WMAP $\Omega_b h^2$ and nuclear uncertainties. It shows that this result is consistent with D/H observations at high redshift and specifically with the last measurement and averaged value

Table 1: BBN results at WMAP $\Omega_b h^2$ from different authors.

Source	Y_p	D/H $\times 10^{-5}$	${}^3\text{He}/H$ $\times 10^{-5}$	Li/H $\times 10^{-10}$
This work	0.2479 ± 0.0004	$2.60^{+0.19}_{-0.17}$	1.04 ± 0.04	$4.15^{+0.49}_{-0.45}$
Cyb03	$0.2484^{+0.0004}_{-0.0005}$	$2.75^{+0.24}_{-0.19}$	$0.93^{+0.055}_{-0.054}$	$3.82^{+0.73}_{-0.60}$
Bur01	-	$2.62^{+0.18}_{-0.22}$	-	-

Cyb03: Cyburt et al. 2003; Bur01 : Burles et al. 2001

of Kirkman et al. (2003). The convergence between these two independent methods seems to confirm this $\Omega_b h^2$ evaluation. Adopting this result as a firm basis, one can draw some consequences on the cosmic chemical evolution and on the global star formation rate history in the Universe. In addition to the high redshift data, the only D/H observations available are i) the protosolar value which is affected by a large error bar, $(2.5 \pm 0.5) \times 10^{-5}$ (Hersant et al. 2001), and ii) the local and present value in the interstellar medium, $(1.52 \pm 0.08) \times 10^{-5}$ (Moos et al. 2002). Accordingly, these observations can only set constraints on the chemical evolution of our Galaxy showing that the star formation history is probably modest and smooth. It is worth noting that, in this context, D has almost not been depleted between Big Bang and the sun birth, typically evolving from 2.60×10^{-5} to 2.5×10^{-5} , during about 10 Gyr, whereas during the last 4.6 Gyr, the mean D/H has decreased from 2.5×10^{-5} to 1.5×10^{-5} . This could seem paradoxical but, taking into account a possible primordial infall, one could alleviate the problem of the proximity between the SBBN and present D/H ratio (Chiappini et al. 2003).

On the other hand, the accumulation of information on the high redshift Universe leads to the conclusion that there was an intense activity in the past compared to present ($z = 0$). Indeed, the cosmic star formation appears to be much higher at high z (Lanzetta et al. 2002, Hernquist and Springel 2003) and moreover, many clues point toward the existence of an early generation of massive stars (Silk 2003, Cen 2003). In this case, the parameters governing global galactic evolution (initial mass function IMF, star formation rate SFR,...) should be reconsidered (see Scully et al. 1997, Daigne et al. 2003, in preparation). In this context, the local D abundance is only representative of local interstellar medium and not of the general star formation history of our Galaxy and a fortiori of the whole Universe. All the more so the FUSE mission has revealed a complex landscape on the D abundance within regions in the solar neighborhood. Indeed, although Moos et al. (2002) did not find any noticeable D variation within 100 pc (local bubble), Hoopes et al. (2003) find a D/H ratio of less than 10^{-5} on longer lines of sight (a few hundreds pc). A third observed line of sight leads to an even lower D abundance, $D/H = 0.52 \pm 0.09 \times 10^{-5}$ (Hébrard and Moos, 2003). Finally, these new results show clearly that it is dangerous to take as a reference any local value of D/H without considering the systematic errors in the determination of the H column densities (Vidal-Madjar and Ferlet 2002). Starting from the primordial D/H deduced from BBN+WMAP, one can predict, according to specific SFR histories versus z (which are probably highly variable from one type of galaxy to the other, see Kauffmann et al. 2003) very different present D abundances in spiral, elliptical galaxies... (Daigne et al. 2003, in preparation).

4.3. Lithium

Contrary to Deuterium, Lithium presents a neat discrepancy. Indeed, our value deduced from WMAP+SBBN is ${}^7\text{Li} = (4.15^{+0.49}_{-0.45}) \times 10^{-10}$, while the most recent observations of Lithium in halo stars lead to the range $\text{Li}/H = (1.23^{+0.68}_{-0.32}) \times 10^{-10}$ (95% c.l.) (Ryan et al. 2000). Hence, this observed Li/H is a factor of 3.4 lower than the WMAP+SBBN value. Even when considering the corresponding uncertainties, the two Li/H values differ statistically ($\sim 3 \times 10^{-7}$ probability). This confirms our (CV) and other (CFO, Cyburt et al. 2003) previous conclusions that the $\Omega_b h^2$ range deduced from SBBN of ${}^7\text{Li}$ are only marginally compatible with those from the CMB observations available by this time. Considering the different nuclear reaction rate analyses involved (NACRE, NB, CFO and DAA) this result is robust with respect to nuclear uncertainties concerning the main SBBN reactions. It is strange that the major discrepancy affects ${}^7\text{Li}$ since it could a priori lead to more reliable primordial value than deuterium, because of much higher observational statistics and an easier extrapolation to primordial values. In Fig. 2 (lower panel) are shown the most recent ${}^7\text{Li}$ observations by Ryan et al. (1999, 2000) as a function of metallicity for old halo stars together with their extrapolated primordial Li/H . The data of Thévenin et al. (2001) and Bonifacio et al. (2002) are also included. This figure emphasizes a strong incompatibility between WMAP+SBBN and measurements made in halo stars. This large difference could have various causes.

The first one, of observational nature, concerns systematic uncertainties on the Li abundances. As said previously, the derivation of the lithium abundance in halo stars with the high precision needed requires a fine knowledge of the physics of stellar atmosphere (effective temperature scale, population of different ionization states, non LTE effects at 1D and further on at 3D, Asplund et al. 2003). However, the 3D, NLTE abundances are very similar to the 1D, LTE results, but, nevertheless, 3D models are now compulsory to extract lithium abundance from poor metal halo stars (see also Barklem et al. 2003).

Secondly, modification of the surface abundance of Li by nuclear burning all along the stellar evolution is discussed for a long time in the literature. There is no lack of phenomena to disturb the Li abundance (rotational induced mixing, mass loss, see Theado and Vauclair 2001, and Pinsonneault et al. 2002). However, the flatness of the plateau over three decades in metallicity and the relatively small dispersion of data represents a real challenge to stellar modeling. New data on ${}^6\text{Li}$ in halo stars are eagerly awaited since they will constrain more severely the potential destruction of ${}^7\text{Li}$ (see Vangioni-Flam et al. 1999). Finally, even taking into account the Li upper limit of the Bonifacio et al. evaluation, the inconsistency persists.

The origin of the discrepancy between the WMAP+SBBN Li/H calculated value and

that deduced from halo stars observations remains a challenging issue. Large systematic errors on the 12 main nuclear cross sections are excluded (DAA) so that new physics has to be invoked if large observational bias can be themselves excluded. Both SBBN and CMB models use the minimal number of potential parameters (even a single one for SBBN) so that their extensions can be considered. For instance, recent theories that could affect BBN include the time variation of coupling constants (Ichikawa & Kawasaki, 2002), the modification of the expansion rate during BBN induced by quintessence (Salati 2002), modified gravity (Serna et al. 2002) or neutrino degeneracy (Orito et al. 2002). These are fundamental issues on which BBN and CMB analyses could shed light.

However, first of all, the influence of *all* nuclear reactions needs to be evaluated before any conclusion.

5. Nuclear uncertainties

The Monte–Carlo calculations using the DAA rate uncertainties introduced above provide the global uncertainties on yields. Here we present the effect of individual rate uncertainties for the main reactions (DAA) but also for other reactions that have been, up to now, neglected. It is well known that the valley shaped curve representing Li/H as a function of η is due to two modes of 7Li production. One, at low η produces 7Li directly via ${}^3H(\alpha, \gamma){}^7Li$ while 7Li destruction comes from ${}^7Li(p, \alpha){}^4He$. The other one, at high η , leads to the formation of 7Be through ${}^3He(\alpha, \gamma){}^7Be$ while 7Be destruction by ${}^7Be(n, p){}^7Li$ is inefficient because of the lower neutron abundance at high density; (7Be later decays to 7Li). Since the WMAP results point toward the high η region, we will pay a peculiar attention to 7Be synthesis.

In Table 2 are represented the maximum uncertainties on 4He , D , 3He and 7Li isotopes arising from the rates of the 10 main nuclear reaction involved in SBBN using the results of DAA. More precisely, X_H (respectively X_L) represents the mass fraction of a given isotope when one of the reaction rate is set to its $+1\sigma$ limit (respectively -1σ limit) and the *maxima* of the quantities $X_H - X_L$ for 4He and $\log(X_H/X_L)$ [i.e. dex] for the other isotopes. By *maximum*, we mean the value having the maximum absolute value when η spans the range between 10^{-10} and 10^{-9} . Variations lower than 0.01 dex (10^{-3} for Y_P) are not shown. From this table, we see that the reactions whose uncertainties affect most 7Li are ${}^2H(p, \gamma){}^3He$, ${}^3H(\alpha, \gamma){}^7Li$, ${}^7Li(p, \alpha){}^4He$ for the low η region and ${}^3He(\alpha, \gamma){}^7Be$ for the (high η) region of interest.

Since we are now interested in the precise determination of the isotopic yields, it is

important to check that besides the 12 main reactions of SBBN the remaining ones are sufficiently known and do not induce any further uncertainties.

Rather than estimating the uncertainties on tens of reaction rates and calculating the corresponding uncertainties on yields, we calculated the yield variations when the rates are scaled by arbitrary factors. If a variation of a reaction rate induces a significant change in the yield, it will be the signal that this reaction should be studied in closer detail and that the rate uncertainty should be calculated. This is based on the prejudice that most of the reactions between $A=1$ and $A=12$ have a negligible influence on isotope yields and hence that they need not be known precisely. To do so, we allowed the rates of the 43 reactions between ${}^2\text{H}(n,\gamma){}^3\text{H}$ and ${}^{11}\text{C}(p,\gamma){}^{12}\text{N}$, whose rate uncertainties are not documented to vary by factors of 10, 100 and 1000 above their nominal rate and calculated the corresponding variation on the ${}^4\text{He}$, D , ${}^3\text{He}$, ${}^7\text{Li}$ yields. (Since the contribution of these reactions to these four isotopes is already considered negligible, it is irrelevant to consider lower rates.) In many cases these factors may be excessive because the rates are based on analysis of existing experimental data or on theory. However, one should note for instance that in the new NACRE compilation (Angulo et al. 1999) several rates differ from the previous ones (CF88) by several orders of magnitude. This is the case, in particular, of the ${}^{10}\text{B}(p,\alpha){}^7\text{Be}$ reaction whose rate has drastically changed between CF88 and NACRE because of new experimental data (Angulo et al. 1993). This has lead to a change of a factor of ≈ 10 in the SBBN ${}^{10}\text{B}$ yield (Vangioni-Flam et al., 2000). In addition, several rates come from estimates that have not been revisited for more than 30 years and could be wrong or obsolete by unpredictable factors. This is might happen, in particular, for reactions involving unstable nuclei. For instance, in another context, the ${}^{18}\text{F}(p,\alpha)$ reaction rate remains uncertain by several orders of magnitude, even at a few 10^8 K (Coc et al., 2000). So in a first step, we use these arbitrary variations, in many cases excessive, to select the most influential reaction rates. In that way we can eliminate from a more detailed study the many reactions whose influence remain negligible even if their rate is increased by a factor as large as 1000. Then, in a second step, having drastically reduced the number of reactions, we discuss their actual nuclear uncertainties.

Table 3 lists the few reactions, for which a variation of their rates by up to an arbitrary factor of 1000 induces a variation of the yields by more than 0.01 dex for ${}^4\text{He}$, D , ${}^3\text{He}$ and ${}^7\text{Li}$. It shows that there are only four reactions that can lead to a factor of at least 3 (0.5 dex) on ${}^7\text{Li}$ yield when their rates are artificially increased by up to a factor of 1000 : ${}^3\text{H}(p,\gamma){}^4\text{He}$, ${}^4\text{He}(\alpha,n){}^7\text{Be}$, ${}^7\text{Li}(d,n){}^4\text{He}$ and ${}^7\text{Be}(d,p){}^4\text{He}$. It remains to check if such a huge increase in these reaction rates is possible. As we will see, this is generally ruled out by existing data.

A factor of ≈ 1000 increases of the ${}^3\text{H}(p,\gamma){}^4\text{He}$ rate would be needed to reduce the ${}^7\text{Li}$

yield by a factor of 3. This is excluded because, since CF88, this reaction cross section has been measured precisely by Hahn et al. (1995) and Canon et al. (2002) over the BBN energy range. The small changes in S -factor brought by these experiments (e.g. a $\approx 40\%$ *reduction* relative to CF88 at a Gamow peak energy corresponding to $T_9 = 1$) rule out any possible influence in BBN. In any case, as seen in Fig. 3, this reaction could only affect the low baryonic density branch, ${}^3\text{H}(\alpha, \gamma){}^7\text{Li}$, and not the WMAP density region.

The reaction rate for ${}^7\text{Li}(\text{d}, \text{n})2{}^4\text{He}$ comes from an analysis by Boyd et al. (1993) of ${}^7\text{Li}$ destruction in BBN. A factor of 100 increase could reduce the ${}^7\text{Li}$ production by a factor of ≈ 3 . Even though, no rate uncertainties are provided by Boyd et al., this seems quite unlikely as their analysis is based on experimental data available in the BBN energy range. Nevertheless, as for the previous reaction this could only influence the direct ${}^7\text{Li}$ formation i.e. the low baryonic density region.

On the contrary, the ${}^4\text{He}(\alpha, \text{n}){}^7\text{Be}$ reaction ($Q=-18.99$ MeV) could affect ${}^7\text{Li}$ production at high η , where it is formed as ${}^7\text{Be}$ (Fig. 3), and through ${}^7\text{Be}$ destruction by the reverse reaction ${}^7\text{Be}(\text{n}, \alpha\gamma){}^4\text{He}$. However, the rate of this latter is negligible compared to the main destruction mechanism : ${}^7\text{Be}(\text{n}, \text{p}){}^7\text{Li}$ (Fig. 3) where a $\ell=0$ resonance dominates while $\ell=0$ is forbidden in ${}^7\text{Be}(\text{n}, \alpha\gamma){}^4\text{He}$ due to the symmetry of the outgoing channel.

The last reaction in Table 3, ${}^7\text{Be}(\text{d}, \text{p}){}^8\text{Be}(\alpha){}^4\text{He}$ is then the most promising in view of reducing the discrepancy between SBBN, ${}^7\text{Li}$ and CMB observations. ${}^7\text{Be}+\text{d}$ could be an alternative to ${}^7\text{Be}(\text{n}, \text{p}){}^7\text{Li}$ for the destruction of ${}^7\text{Be}$ (see Fig. 3), by compensating the scarcity of neutrons at high η . Figure 4 shows the effect of an increase of the ${}^7\text{Be}(\text{d}, \text{p})2{}^4\text{He}$ reaction rate: a factor of $\gtrsim 100$ could alleviate the discrepancy. The rate for this reaction (CF88) can be traced to an estimate by Parker (1972) who assumed for the astrophysical S -factor a constant value of 10^5 keV.barn. This is based on the single experimental data available (Kavanagh, 1960). To derive this S -factor, Parker used the measured differential cross section at 90° and assumed isotropy of the cross section. Since Kavanagh measured only the p_0 and p_1 protons (i.e. feeding the ${}^8\text{Be}$ ground and first excited levels), Parker introduced an additional but arbitrary factor of 3 to take into account the possible population of higher lying levels. Indeed, a level at 11.35 MeV is also reported (Ajzenberg-Selove 1988). This factor should also include the contribution of another open channel in ${}^7\text{Be}+\text{d}$: ${}^7\text{Be}(\text{d}, \alpha){}^5\text{Li}$ for which no data exist. The experimental data (Kavanagh, 1960) is displayed in Fig. 5 showing the two expected resonances at 0.7 and 1.2 MeV (Ajzenberg-Selove, 1988). A third one at 0.6 MeV is excluded because of isospin selection rules. ${}^7\text{Li}$ and ${}^7\text{Be}$ Big Bang nucleosynthesis take place when the temperature has decreased below $T_9=1$. The Gamow peaks for $T_9=1$ and 0.5 displayed in Fig. 5 show that there are no experimental data at SBBN energies. A seducing possibility to reconcile, SBBN, ${}^7\text{Li}$ and CMB observations would then be

that new experimental data below $E_d = 700$ keV ($E_{cm} \approx 0.5$ MeV) for ${}^7\text{Be}(d,p){}^4\text{He}$ [and ${}^7\text{Be}(d,\alpha){}^5\text{Li}$] would lead to a sudden increase in the S -factor as in ${}^{10}\text{B}(p,\alpha){}^7\text{Be}$ (NACRE). This is not supported by known data, but considering the cosmological or astrophysical consequences, this is definitely an issue to be investigated. Accordingly, an experimental study of this reaction will be performed soon at Louvain la Neuve.

6. Conclusions

In conclusion, the recent WMAP experiment has to be acknowledged as a great progress, specifically concerning the evaluation of the baryon content of the Universe. This leads the nuclear astrophysicists to refine their calculations. We have improved SBBN calculations taking into account a new nuclear physics analysis (DAA) of SBBN reaction rates. The consistency between WMAP results and D/H data from the remote cosmological clouds on the line of sight of high redshift quasars strengthens the deduced baryonic density. However, a significant discrepancy is observed for lithium. Nuclear effects, as in particular higher ${}^7\text{Be}+d$ reaction rates (see above), could reconcile calculations and observations. If not, new and exciting astrophysical or physical effects will have to be considered.

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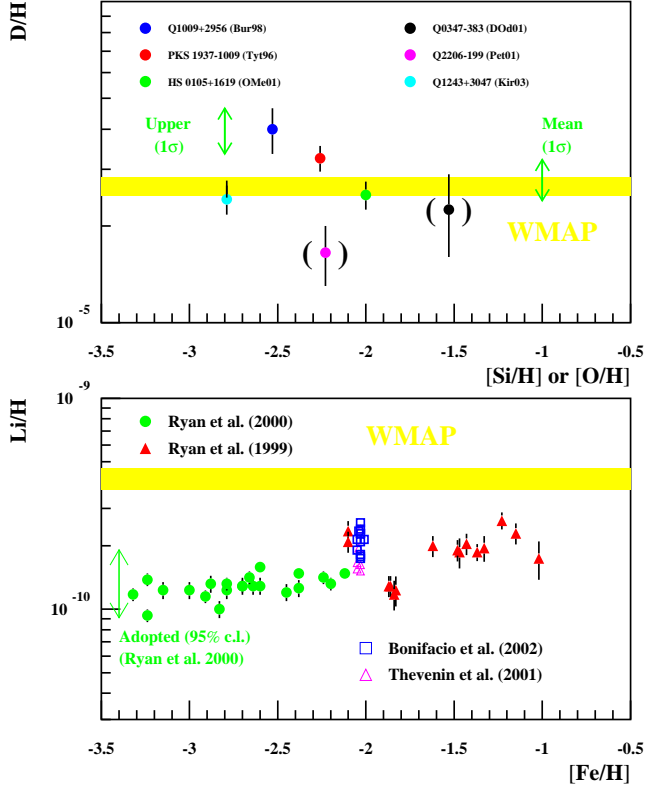


Fig. 2.— Observed abundances as a function of metallicity from objects which are expected to reflect primordial abundances. Upper panel : observed D abundances in cosmological clouds (parenthesis indicate less established observations.) The mean observational value (Kirkman et al. 2003) and the highest observed value used in CV are shown by arrows. The horizontal stripe represents the $(1-\sigma)$ $\Omega_b h^2$ limits provided by WMAP+BBN. Lower panel : observed 7Li abundances from Ryan et al. (1999; 2000) and extrapolated primordial abundance Ryan et al. (2000) shown by an arrow. Li/H observations in a globular cluster at $[Fe/H]=-2$ (Thévenin et al. 2001; Bonifacio et al. 2002) are also displayed. The horizontal stripe represents the $(1-\sigma)$ $\Omega_b h^2$ limits provided by WMAP+BBN.

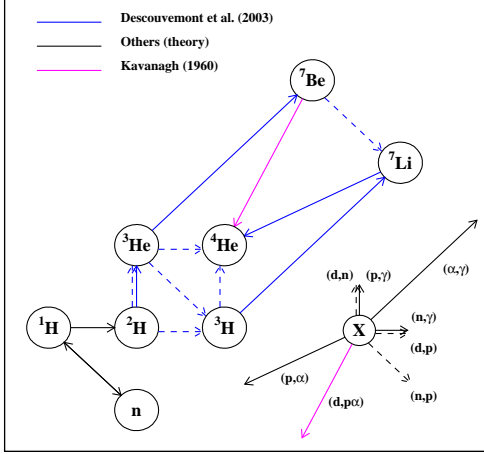


Fig. 3.— The 12 main SBBN reactions plus ${}^7\text{Be}(\text{d},\text{p})2{}^4\text{He}$.

Table 2: Influential reactions and their sensitivity to nuclear uncertainties for the production of ${}^4\text{He}$, D , ${}^3\text{He}$ and ${}^7\text{Li}$ in SBBN.

Reactions	${}^4\text{He}$	D	${}^3\text{He}$	${}^7\text{Li}$
	$(X_H - X_L)_{max}$	$(\log(X_H/X_L))_{max}$		
${}^2\text{H}(\text{p},\gamma){}^3\text{He}$	.-	-0.030	0.022	0.034
${}^2\text{H}(\text{d},\text{n}){}^3\text{He}$	.-	-0.009	0.007	0.011
${}^2\text{H}(\text{d},\text{p}){}^3\text{H}$	.-	-0.008	-0.008	0.003
${}^3\text{H}(\text{d},\text{n}){}^4\text{He}$	.-	.-	-0.003	-0.004
${}^3\text{H}(\alpha,\gamma){}^7\text{Li}$	.-	.-	.-	0.038
${}^3\text{He}(\text{d},\text{p}){}^4\text{H}$	0.0022	.-	-0.018	-0.017
${}^3\text{He}(\text{n},\text{p}){}^3\text{He}$	.-	.-	-0.006	-0.004
${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$	.-	.-	.-	0.049
${}^7\text{Li}(\text{p},\alpha){}^4\text{He}$	.-	.-	.-	-0.039
${}^7\text{Be}(\text{n},\text{p}){}^7\text{Li}$	.-	.-	.-	-0.003

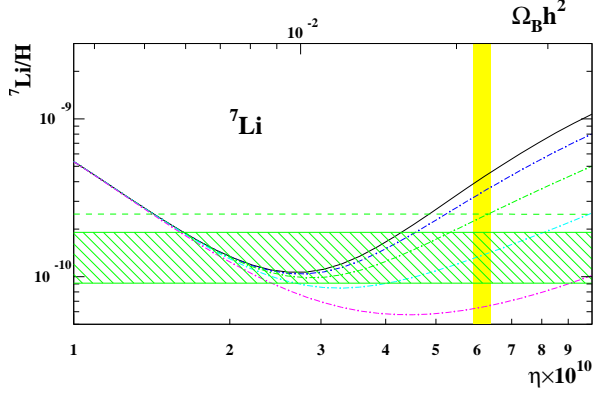


Fig. 4.— Same as Figure 1, lower panel, but including the effect of ${}^7\text{Be}(d,p){}^{24}\text{He}$ rate variations while other reaction rates are set to their nominal values. The solid curve is the reference where the ${}^7\text{Be}(d,p){}^{24}\text{He}$ rate from CF88 is used, while the dash-dotted curves correspond to an increase of the rate by factors of 30, 100, 300 and 1000.

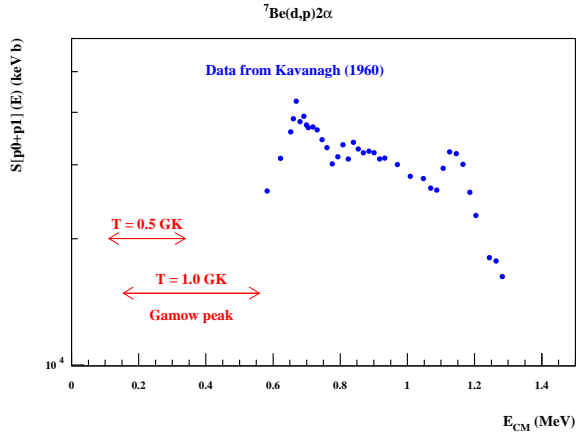


Fig. 5.— The only experimental data available for the ${}^7\text{Be}(d,p){}^{24}\text{H}$ reaction from Kavanagh (1960). The displayed S -factor is calculated as in Parker (1972) from the differential cross section at 90° ($\times 4\pi$) leading to the ground and first ${}^8\text{Be}$ excited states. Note that no data is available at SBBN energies as shown by the Gamow peaks for $T_9 = 1$ and 0.5.

Table 3: Test of yield sensitivity to reactions rate variations: factor of 10,100,1000 (see text).

Reaction	Ref.	${}^4\text{He}$	D	${}^3\text{He}$	${}^7\text{Li}$
		$(X_H - X_L)_{max}$	$(\log(X_H/X_L))_{max}$		
${}^2\text{H}(n,\gamma){}^3\text{H}$	Wag69	0.003	-.-	-.-	-.-
		0.025	-0.010	-.-	-0.011
		0.110	-0.073	-0.048	-0.078
${}^3\text{H}(p,\gamma){}^4\text{He}$	CF88	-.-	-.-	0.012	0.074
		0.003	-0.017	0.055	0.26
		0.018	-0.058	0.14	-0.56
${}^3\text{He}(t,np){}^4\text{He}$	CF88	-.-	-.-	-.-	-.-
		-.-	-.-	-.-	-0.012
		-.-	0.053	-0.026	-0.092
${}^4\text{He}(\alpha,n){}^7\text{Be}$	Wag69	-.-	-.-	-.-	-0.056
		-.-	-.-	-.-	-0.36
		-.-	-.-	-.-	-1.1
${}^7\text{Li}(d,n){}^2{}^4\text{He}$	Boy93	-.-	-.-	-.-	-0.10
		-.-	-.-	-.-	-0.44
		-.-	-.-	-.-	-1.1
${}^7\text{Li}(t,2n){}^2{}^4\text{He}$	MF89	-.-	-.-	-.-	-.-
		-.-	-.-	-.-	-.-
		-.-	-.-	-.-	-0.055
${}^7\text{Be}(d,p){}^2{}^4\text{He}$	CF88	-.-	-.-	-.-	-0.047
		-.-	-.-	-.-	-0.34
		-.-	-.-	-.-	-1.0

Wag69: Wagoner 1969;

CF88: Caughlan & Fowler 1988;

Boy93: Boyd et al. 1993; MF89: Malaney & Fowler 1989.